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FUNDAMENTAL ASPECTS OF SUPERSONIC COMBUSTION

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FUNDAMENTAL ASPECTS OF SUPERSONIC COMBUSTION

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ABSTRACT

The application of turbulence theory to the design of supersonic combustors has been investigated both experimentally and theoretically. Experimental studies carried out in the 150 mm shock tunnel have shown that a vortex fuel injector can release the heat extremely rapidly (≈ 200 mm) at a stream velocity of about 3000 m/s. A rapidly responding sampling probe suitable for monitoring gas composition variations within $\frac{1}{4}$ millisec. has also been developed. The theoretical studies have led to the prediction of an important limitation on the performance of supersonic burners due to the fundamental requirement to produce turbulent kinetic energy at the expense of stream energy.

INTRODUCTION

The application of turbulence theory to the design of practical gas dynamic systems such as combustors has been previously limited by mathematical complexity. A new technique based on turbulent energy balance principles has been developed and is being applied to supersonic combustion systems. An extensive report presenting the theory has recently been prepared (Ref. 1) and the details will not be repeated herein. Earlier experimental work is given in Ref. 2 and some current investigations and results are described below.

Experimental Studies

The mixing and combustion of hydrogen in a supersonic airstream is being investigated in a two dimensional Mach 3.5 test section. The stagnation conditions being used are 5000°K at 20 MN/m^2

corresponding to a flight Mach number of 10. These conditions are obtained using a 150 mm. combustion driven shock tunnel, operating at the tailored interface condition. A computer programme has been developed which accurately predicts the performance of the tunnel. This can be used quite reliably to give the required initial conditions for any desired operating condition (Fig. 1). These programmes can be easily extended to predict the test section conditions for isentropic nozzle operation. This will enable the nozzle efficiency to be determined which can then be used to give an accurate determination of test section conditions prior to mixing and combustion.

The available test time for tailored operation is $\simeq 3$ msec, and the minimum time required for mixing and combustion to be established in the 750 mm long test section is $\simeq 1$ msec. Driver gas contamination has been shown by various workers to affect test times by as much as an order of magnitude depending on the gases used, when operating close to the tailored condition. For this reason a detailed study of the two suggested contamination mechanisms has been carried out, and it has been established both theoretically and experimentally that within the present operating range, using combustion driving, driver gas contamination is not a serious problem. For the particular dimensions and operating conditions of the Sheffield tunnel, the primary shock Mach number for tailoring is within the range 10.9-9.6, whereas contamination due to transmitted shock bifurcation occurs only for Mach numbers greater than 12.4; and contamination due to contact surface instability for Mach numbers greater than 12.7.

The current experimental programme is concerned with the mixing and combustion associated with mid-stream axial injection of hydrogen into a Mach 3.5 airstream. The present injector configuration was designed to promote rapid turbulent mixing, and

the turbulence level was chosen which was compatible with the aerodynamic blockage ratio. The turbulence is generated in an unconventional wake region by the production and interaction of swiss-roll type vortices formed each side of the rear ward facing delta shaped louvres. The hydrogen, at room temperature, is injected into this turbulent region through holes situated beneath each louvre in the base of the wedge.

The formation and interaction of the 24 vortices ensures a rapid conversion of pressure energy into turbulent energy. The initial eddies formed by this will be small and of high frequency, hence they will dissipate their turbulent energy much faster than would the initial eddies formed by a conventional wedge shaped bluff body of equivalent blockage. Therefore for a given throughput the mixing and subsequent combustion will take place at a faster rate than that obtained using either a wedge or concentric injection system.

Measurements of wall static pressures in the test section for various hydrogen flow rates indicate that rapid mixing and subsequent heat release is taking place.

Fig. 2 shows typical static pressures obtained with and without combustion. St 1 is positioned 15 mm in front of the injectors leading edge and gives the undisturbed static pressure. St 2 is positioned ~65 mm downstream of the injection point with St 3 ~500 mm from the injection. Run number MJ4/19 shows the pressures obtained with an equivalence ratio of 0.057, and the pressure at St 2 is seen to be high and very steady when compared with that of run number MJ4/24 in which no hydrogen was injected. The oscillatory nature of St 2 is attributed to the fact that the leading edge shock is reflected from the wall in the vicinity of St 2 for the

no combustion case. The interaction of the shock and the boundary layer leads to these pressure fluctuations. When combustion is occuring behind the injector the increased pressure 'pushes' the leading edge shock further forward and no pressure fluctuations are seen.

Fig. 3 shows the static pressures measured for various equivalence ratios. It should be pointed out that the position of the pressure maximum and the shape of the curves, are those found using only 3 pressure transducers. However the importance of these curves is that they do show the general form of the static pressure distribution. This general form indicates that following injection there is a comparison zone followed by a re-expansion zone. This compression zone followed by the combined effect of heat and mass addition, and the theory which shows an equivalence between heat and mass sources states that if $\frac{\partial \dot{Q}}{\partial x}$ is large steep compression will result, and if the compression waves coalesce shock waves may even be formed. In an attempt to indicate the relative contribution of heat and mass addition tests were carried out using N_2 as an inert test gas and injecting H_2 into it. A comparison of the pressures obtained is shown in Fig. 4. This shows that a significant proportion of the compression is due to heat release. Hence it may be concluded that mixing and subsequent combustion occurs within a very short distance of injection. Making a simplifying assumption that the pressure disturbances due to mass addition remain constant for each case, and that the pressure disturbances due to heat release is superimposed on this. Then the form of the pressure distribution fits in very well with the concepts of perfectly stirred reactors and plug flow reactors. In the well stirred region $\frac{\partial \dot{Q}}{\partial x}$ increases rapidly until a maximum value is reached. Then after entering the plug flow region $\frac{\partial \dot{Q}}{\partial x}$ will decrease slowly until combustion is completed. The

pressure rise expected for complete combustion of stoichiometric hydrogen at test section conditions has been calculated using Mollier charts, and together with the wall friction drag pressure rise is shown on Fig. 3 as the equilibrium pressure.

The close agreement is perhaps a little surprising for such a large difference in equivalence ratios. It should be noted that the equivalence ratios were computed assuming no dissociation of the test air in the nozzle. In actual fact under these conditions there will be substantial oxygen depletion due to the formation of oxides of nitrogen.

The dotted line on the graph shows the results of an analytical approach for mid-stream axial injection of hydrogen in a constant area Mach 2 airstream, obtained by Slutsky and Tamango. The agreement in overall shape is most encouraging. The difference in pressure levels is probably due to the different initial conditions and the fact that the analysis is based on an inviscid theory.

These experimental results have shown the type of pressure profiles to be expected in actual scramjet combustors employing similar geometry. An increase in test section instrumentation will help give a more detailed picture of the complex phenomena of mixing and combustion under these conditions.

One addition ot the test section instrumentation is to be a mid-stream probe capable of measuring pressure and changes in gas composition simultaneously, having a response time of $\approx \frac{1}{4}$ msec.

This probe has been developed from the design proposed by R.J. Stalker, for detecting contamination in shock tunnels.

The probe consists essentially of a heat exchanger and plenum chamber whose function is to supply the sampled gas stream at a constant temperature for re-expansion through a sonic orifice into

a chamber.

The pressure in the cavity at any instant is given by

$$P = \frac{mRT_c}{V_c}$$

and differentiating w.r.t. time, for constant temperature

$$\frac{dP}{dt} = \frac{dm}{dt} \cdot \frac{RT_c}{V_c} \qquad \ldots. (1)$$

The mass flow rate through the sonic orifice is

$$\frac{dm}{dt} = K \quad \rho_e a_e A_e \qquad \ldots. (2)$$

and taking conditions in the plenum as local stagnation conditions

$$\frac{\rho_e}{\rho_o} = \left(\frac{2}{\alpha + 1}\right)^{\frac{1}{\alpha - 1}} ; \quad \frac{a_e}{a_o} = \left(\frac{2}{\alpha + 1}\right)^{\frac{1}{2}} \text{ and } \rho_o = \frac{P_s}{RT_o}$$

$$\therefore \rho_e a_e = \left(\frac{2}{\alpha + 1}\right)^{\frac{\alpha + 1}{2(\alpha + 1)}} \frac{P_s a_o}{RT_o}$$

substituting in (2) gives

$$\frac{dm}{dt} = K\left(\frac{2}{\alpha + 1}\right)^{\frac{\alpha + 1}{2(\alpha + 1)}} \frac{P_s a_o}{RT_o} \cdot A_e \qquad \ldots. (3)$$

substituting (3) in (1) gives

$$\frac{dp}{dt} = \left(\frac{2}{\alpha + 1}\right)^{\frac{\alpha + 1}{2(\alpha - 1)}} \frac{K.A_e.T_c}{T_c.V_c} \cdot P_s.a_o$$

and because of low mass flow rates and high thermal mass of the probe and heat exchanger we assume that $\frac{T_c}{T_o}$ is constant, then

$$\frac{dp}{dt} = B. \; P_s. \; a_o$$

so if P and P_s are measured, any change in the slope of P without

a corresponding change in P_s means a_0 has changed, and at constant temperature this means a change in molecular weight.

Plate 1 shows an exploded view of the probe being used at Sheffield. The heat exchanger and plenum chamber constitute the horizontal piece together with a miniature transducer for measuring Ps. The gas flows through the sonic orifice into the vertical chamber, which is also fitted with a transducer to monitor $\frac{dp}{dt}$. The critical factors in the design of this probe have been found to be:-

1. Sampling time - the gas must continue to flow into the chamber for the total test time under investigation. This 'filling' time is found to be dependent on the ratio of chamber volume to orifice area.

2. Response time - for good resolution the response time must be an order of magnitude below the sampling time. A simple RC analogue shows that the response time of the probe is directly proportional to the ratio of plenum + heat exchanger volume to chamber volume. This design restraint may be overcome by having a bleed from the plenum.

This probe has been tested in the Mach 3.5 test section, and has been used to verify the contamination data. The next phase of the experimental programme includes the utilisation of this probe to investigate the nature and position of the mixing and combustion zones, both in the near flow field and in the far flow field downstream of the injector. This, together with extra static pressure transducers will be used in a more detailed experimental investigation of the mixing and combustion of hydrogen in a supersonic airstream.

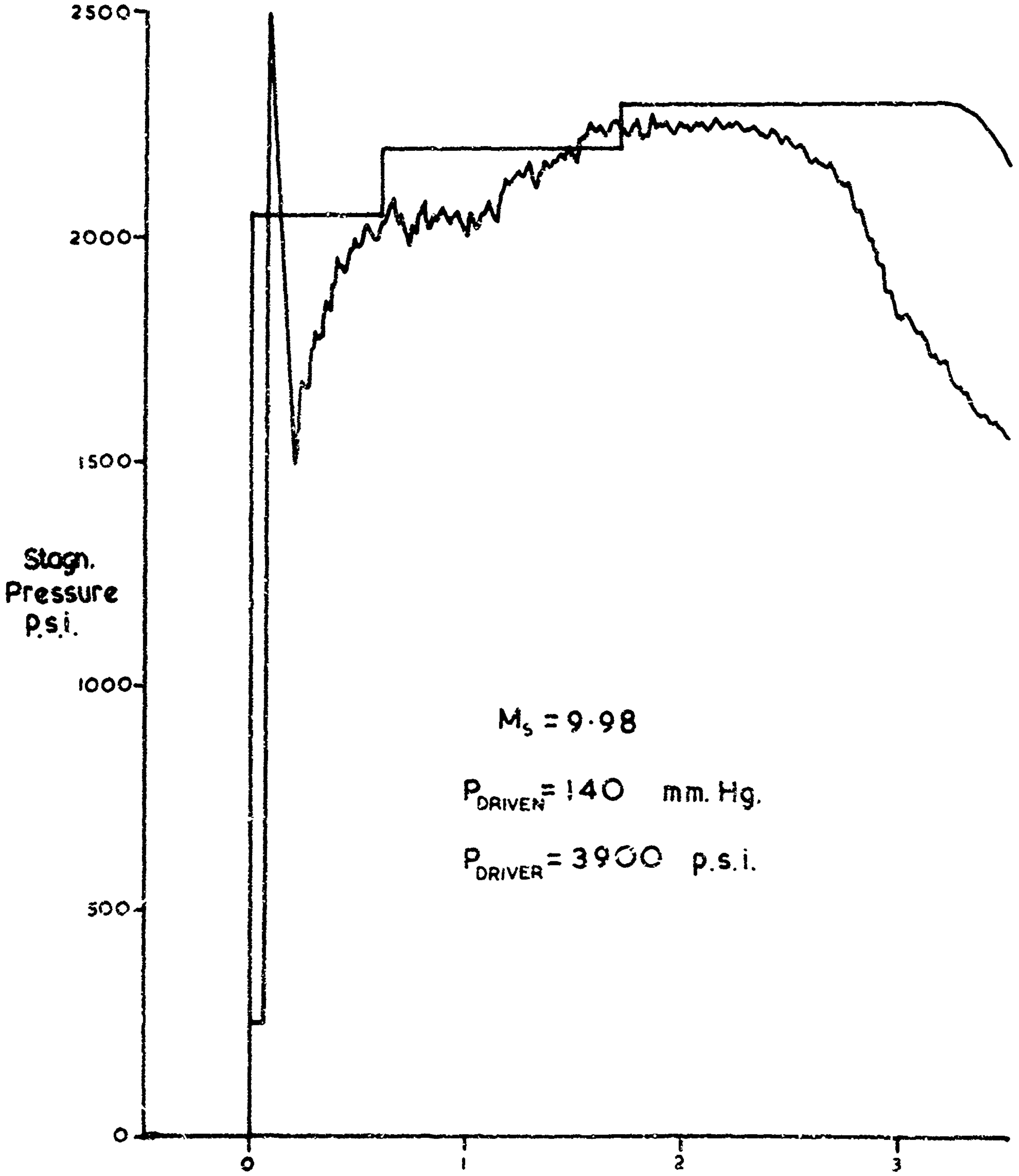
References

1. J. Swithenbank, "Combustion Fundamentals", Report No. HIC 150, Dept. of Chem. Eng., Sheffield University.

2. R.J. Parsons, "Supersonic Combustion Research Techniques in a Hypersonic Shock Tunnel", Ph.D. Thesis, 1969, Sheffield University.

FIG. 1.

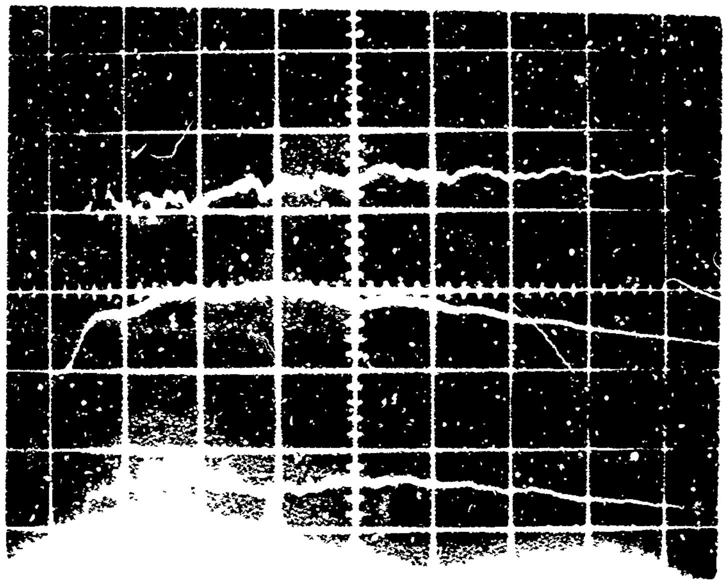
COMPUTED AND MEASURED PRESSURES



STATIC PRESSURE RECORDS

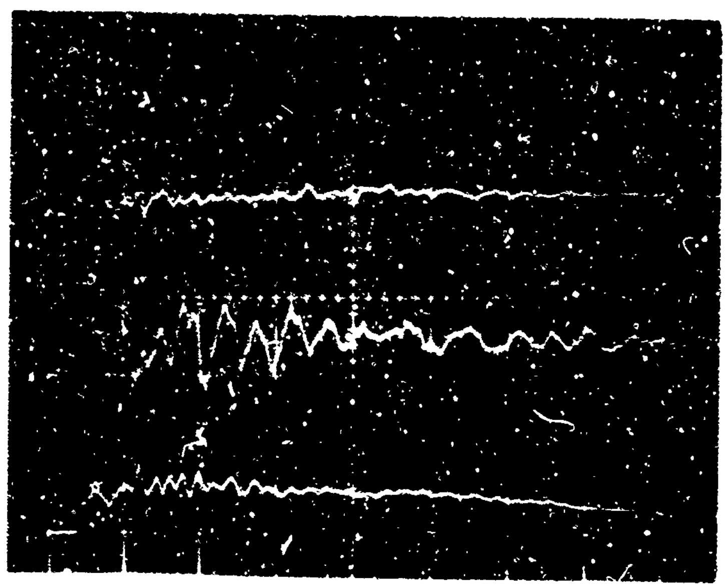
MJ4/19 — Combustion

50 p.s.i/div.



MJ4/24 — No Combustion

50 p.s.i./div.



0·5 msec/div.

FIG. 3.

STATIC PRESSURE DISTRIBUTION 1·5 MSEC. AFTER STARTING

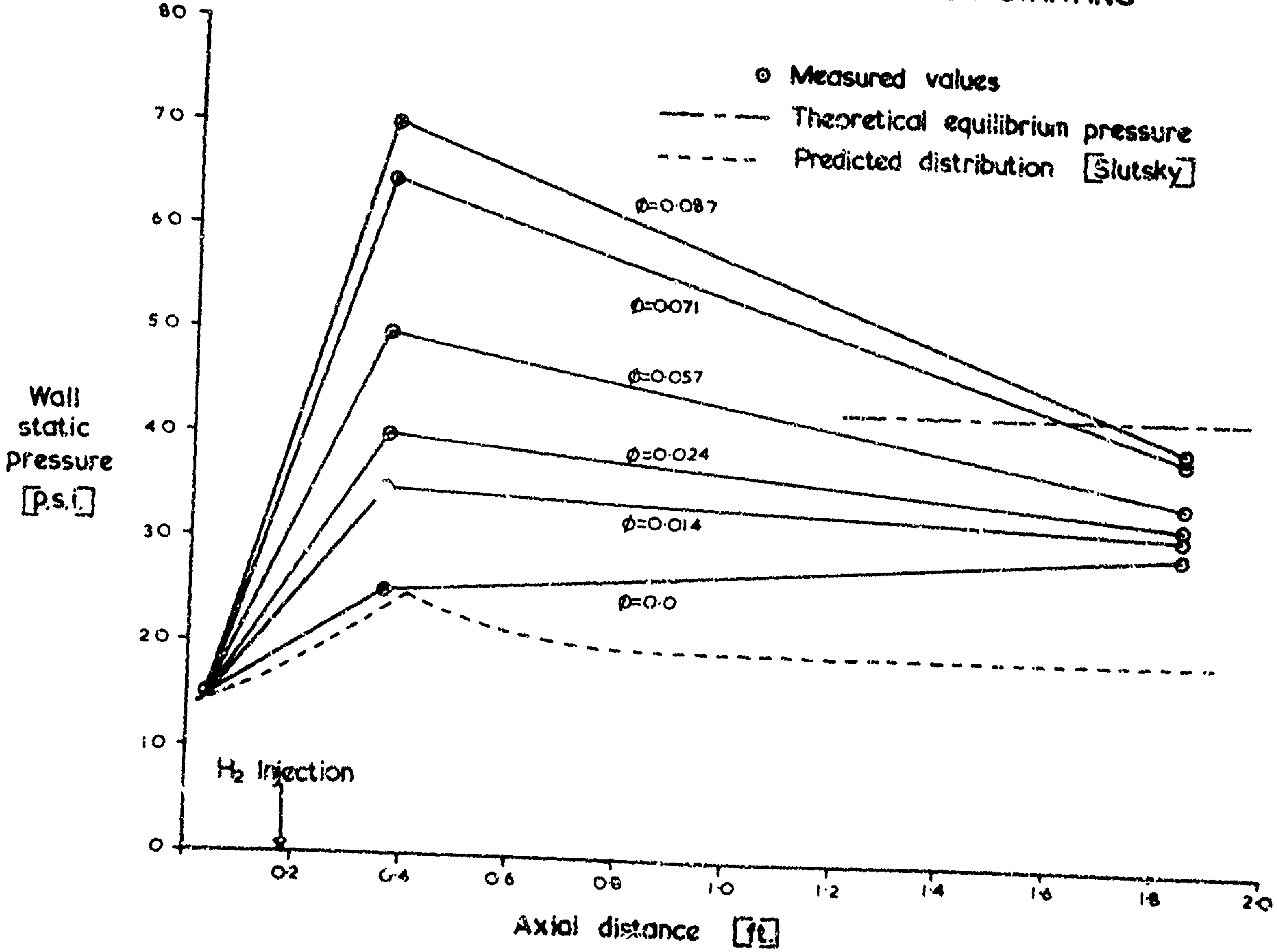
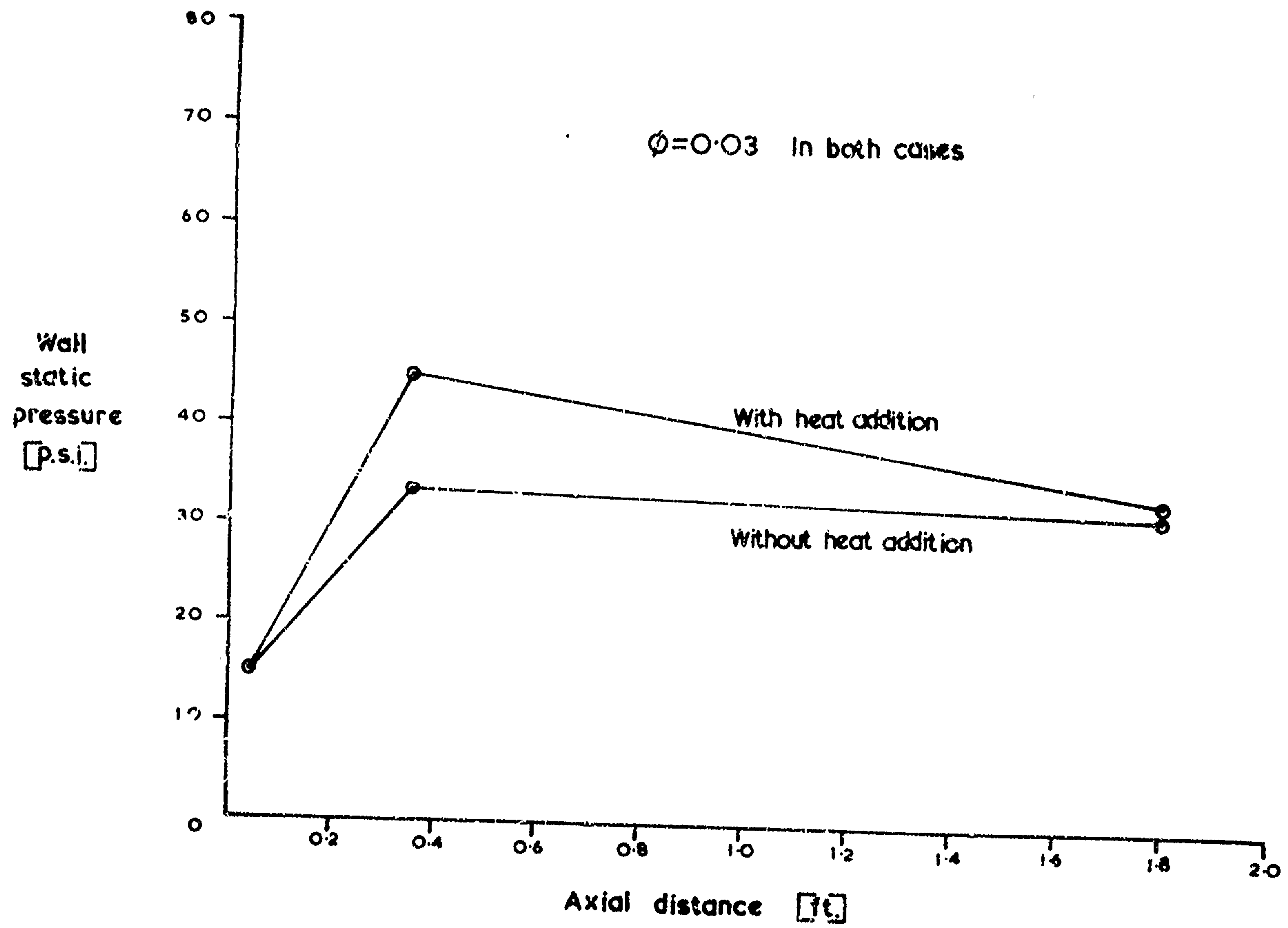
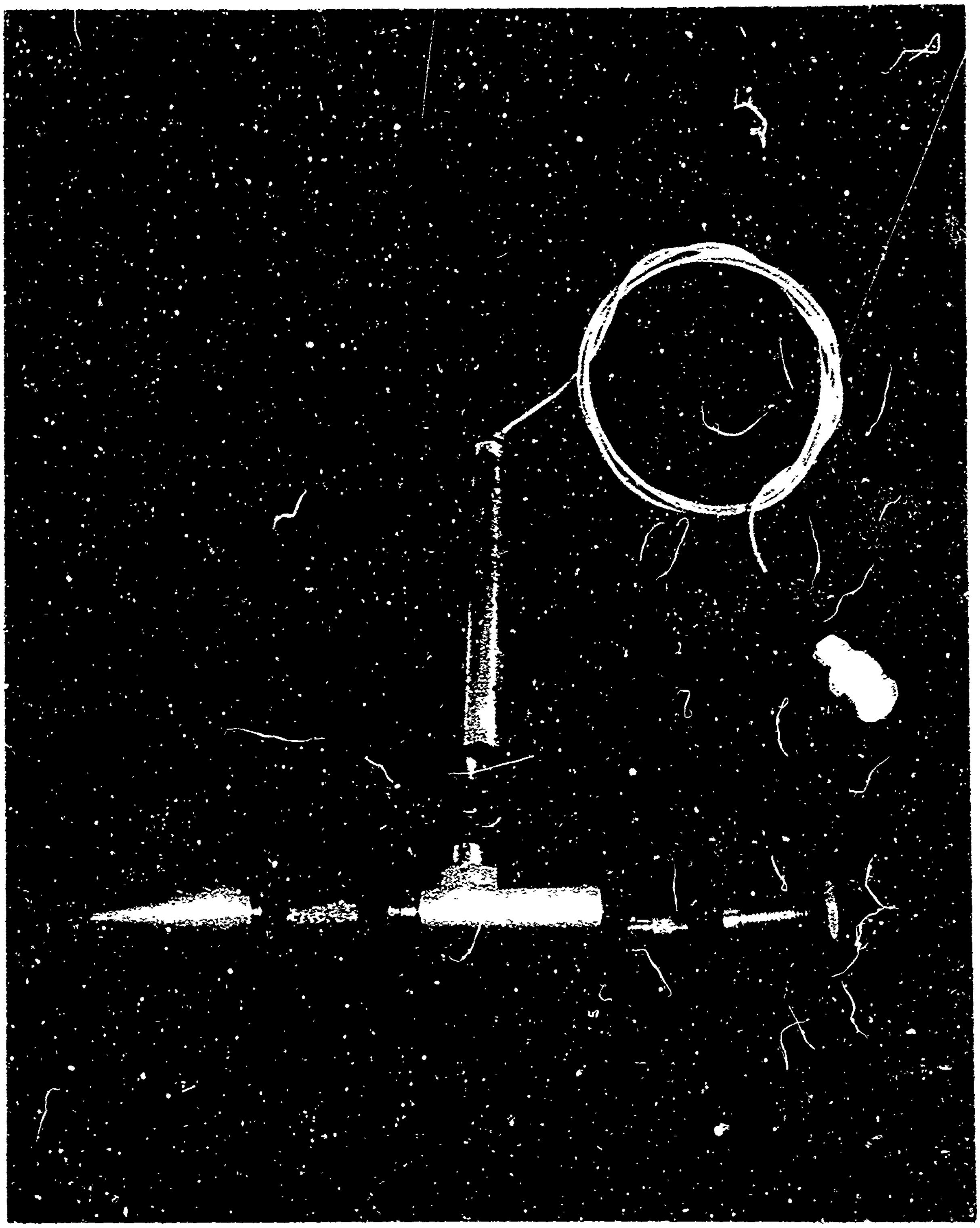


FIG. 4. STATIC PRESSURES WITH AND WITHOUT HEAT ADDITION





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